

On Integration of Mirror Collector and Stirling Engine for Solar Power System

B.F. Yousif, Ammar Al-Shalabi, and Dirk G. Rilling

Abstract In the current work, several types of solar collectors, i.e. parabolic, cylindrical, and mirrors, were designed and fabricated. The aim of this study is to integrate the optimum collector with Stirling engine in Malacca city, Malaysia. Stirling engine was designed using CATIA software. The solar collectors were tested for several sunny days and the temperature in the focus point was measured. Comparing the experiment results shows that mirror solar collector introduces highest temperature among others, which was about 190°C. According to that temperature, the Stirling engine has been designed in bore piston dimension of 50 mm. Alpha Stirling engine type was selected for this purpose, which may run in this range of temperature.

Keywords Solar power · Collector · Stirling engine · Solar energy

1 Introduction

Nowadays, need of energy and increasing environmental awareness, alternatives to fossil fuels are being of high concern to many engineers. One of the alternative resources is solar energy, which are free, clean and free of environmental pollution [10, 11]. Solar energy is simply the energy which is produced directly from the sun light. There are many reported methods to implement the solar energy for useful life applications, such as solar water heater system [7], solar dryer system [7], and solar power generator [7, 15, 9, 2, 12].

In the last decades, there have been many research attempts to run the external combustion engines, such as Stirling engine, using solar energy [3], it has been reported by Abdullah et al. [2] that the maximum temperature gain is about

B.F. Yousif (✉)

Faculty of Engineering and Technology, Malacca Campus, Multimedia University,
75450 MMU, Malacca, Malaysia
e-mail: Belal.f.yousif@mmu.edu.my

70°C. Using hot water as a heat resource [2]. Meanwhile, in using mirror collectors, high temperature may be obtained [7, 12]. Currently, Stirling engine is one of the most efficient devices for converting solar heat into mechanical work and an ideal candidate for harvesting the power from the sun [15].

Integrating Stirling engine with high temperature solar collector is carried out in Malacca city in Malaysia where there is only one season which is always hot. In the present work, several types of solar collectors (mirror collector, parabolic, and cylindrical trough) are designed, fabricated and tested. Mirror collector is selected as the best to be integrated with the proposed Stirling engine.

2 Solar Collector Design

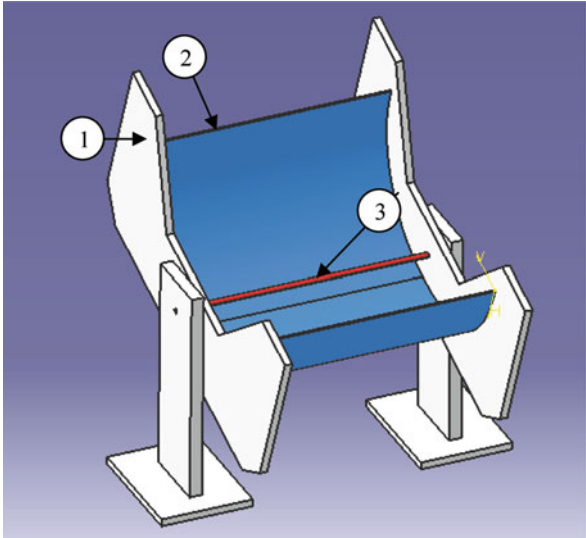
Generally, there are two main parts of concentrating collector, concentrator and receiver. Concentrator can be cylindrical or parabolic, continuous or segmented. Receiver can be convex, flat, cylindrical or concave, and can be covered with glazing or uncovered. Some important parameters are to be considered in the design of concentrating collector such as concentrating ratio, rim angle, reflective surface, receiver material, collector orientation and mode of tracking.

Concentrating ratio is the ratio of aperture area (opening area of solar collector) to receiver area; it can vary over several orders of magnitude. An increased concentrating ratio corresponds to increased temperature at which energy can be delivered but this increases the requirement for precision in concentrator quality and positioning of the concentrator [6]. Rim angle is defined as the angle between the incident ray and the reflected ray. Materials used in the collector affect its performance. For concentrator, material with better reflectance is preferred since it needs to reflect as much solar radiation as possible. And, it must have long life and low cost because the reflecting surface may deteriorate when exposed to weather. The common materials used are, for instance, polished aluminum surface and iron glass mirror. The essential task of a receiver is to absorb maximum amount of reflected solar energy and transfer it to heat with minimum losses to the surrounding. The commonly used materials are copper and brass. Concentrating collector can be orientated east-west tracking north-south or orientated north-south tracking east-west [11].

2.1 Parabolic Trough Collector

The scale model of this collector (Fig. 1) uses a piece of shining aluminum shield as a concentrator (reflective surface) while a solid brass rod as the receiver. These two materials are selected due to their low cost and availability. Aluminum shield is easy to fabricate and form into parabolic shape to develop the parabolic trough. Both materials have been cleaned before put into use. The trough is made base on a parabola function,

Fig. 1 Scale model of parabolic trough collector in 3-D view in catia.
1. Polystyrene, 2. Aluminum shield, 3. Brass rod



$$y = \frac{x^2}{4f}$$

where y and x are the coordinates of trough and f is its focal point location from the vertex of the parabolic trough. This function is used to calculate the size of the trough when the focal point location is selected [4]. A focal point of 5.08 cm from vertex is selected. The receiver (brass rod) is placed at this position, creating a focal line. At this position, it is near to the trough’s surface, thus reducing the heat convection loss between them since the gap is small. To reduce heat conduction loss from the receiver, a brass rod of less surface area is selected. By reducing overall heat loss, a higher temperature can be obtained at the receiver.

The frame and support of the parabolic trough are made of polystyrene due to its low cost, light weight, and moreover it is easy to fabricate. In order to obtain maximum possible temperature and to save cost, the parabolic trough is manually adjustable to track the sun motion for sharp focal on the receiver. The designed collector is a single axis tracking type. Thus, the scale model of this collector is orientated north-south tracking east-west. The dimension of aluminum shield and solid brass rod are shown in Table 1 and the parameter of parabolic trough collector is shown in Table 2.

Table 1 Dimension of aluminum shield and solid brass rod

Part	Diameter (cm)	Length (cm)	Width (cm)
Aluminum shield	–	38.1	60.96
Solid brass rod	0.8	81.3	–

Table 2 Parameter of parabolic trough collector

Parameter	Unit
Rim angle	127°
Aperture area	1548.38 cm ²
Concentration ratio	16:1

2.2 Iron Glass Mirror Collector

The glass collector (Fig. 2) uses 81 pieces of iron glass mirror as a concentrator. The concentrator is a point focusing type. A copper plate is used as receiver. The dimension of iron glass mirror and copper plate is shown in Table 3 and the parameter of parabolic trough collector is shown in Table 4.

The mirrors are used to stimulate the paraboloid shape to focus the reflected ray to receiver as one focal point according to the law of reflection. Figure 3 explains that the angle of incidence at which a ray intersects a reflective plane is equal to the

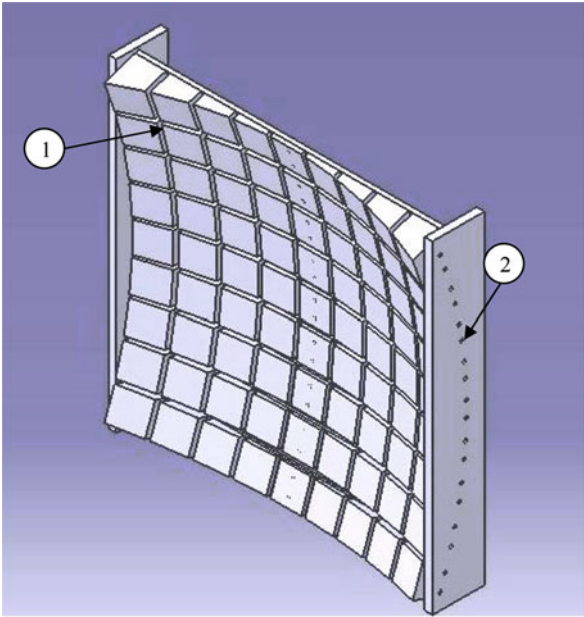


Fig. 2 Iron glass mirror collector. 1. Concentrator frame in paraboloid shape to attach 81 pieces iron glass mirrors, 2. Support plate

Table 3 Dimension of iron glass mirror and copper plate

Part	Length (cm)	Width (cm)	Quantity (pcs)
Iron glass mirror	14	10	20
Copper plate	14	10	1

Table 4 Parameter of parabolic trough collector

Parameter	Unit
Rim angle	37°
Aperture area	2800 cm ²
Concentration ratio	20:1

Fig. 3 Law of reflection

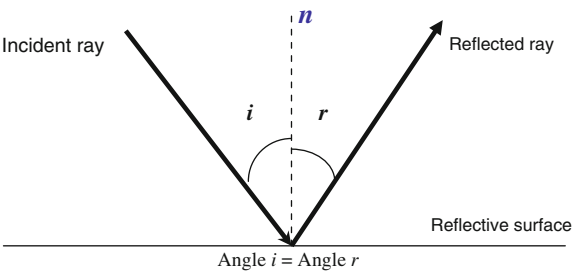
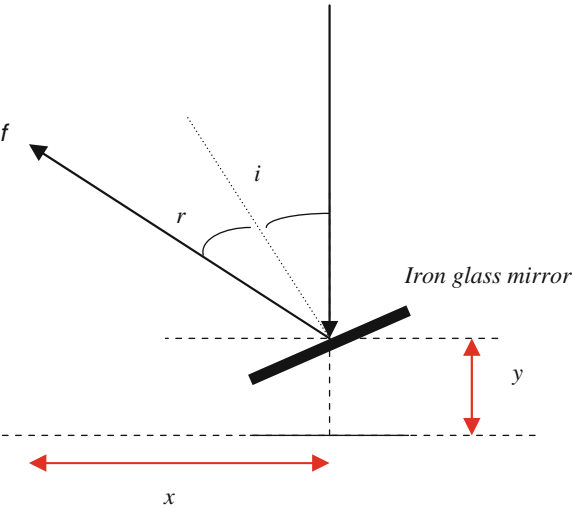


Fig. 4 Reflection of incident ray from iron glass mirror to focal point



angle of reflection at which the ray is reflected [5]. Figure 4 shows the reflection of incident ray from iron glass mirror to focal point.

To simulate the paraboloid shape, each mirror is arranged by having five mirrors in a row and each row is stacked above one another, giving a total of four rows. A manually adjustable support behind each mirror allows the mirrors to focus the sun ray on the receiver according to sun motion. A parabola function is used to calculate the exact position of each mirror to be attached to a frame by setting fixed value for coordinate x and focus point f [4].

3 Stirling Engine

Commonly, solar powered Stirling engines are classified according to the operating temperature difference, regardless of kinematics or “free piston”, non physical linkage; High Differential Temperature Stirling Engine (HDTs) and Low Differential Temperature Stirling Engine (LDTS) [1]. These engines are used to power application like water pump, electricity generator or even refrigeration cooler [8].

In this paper, an alpha-type engine is suggested. A simple thermodynamic model is set up to obtain the necessary basic design parameters for the Stirling engine. Although Stirling engine operates in a close cycle with consistent gas composition, it is still very difficult to simulate the actual process as the working fluid travels across different chambers and has varying heat transfer rate; therefore a standard ideal gas cycle is considered as an approximate substitute to the real cycle [17]. Figure 5 is used to develop the energy equation and subsequently the thermodynamic model. The separated expansion cylinder is the sole power provider for the focus of analysis, thus simplifying the task.

The energy equation can be simplified as the gross heat input. The Q_H and Q_L describe the heat flux entering and leaving the thermal engine.

$$\text{Energy equation: } Q_{in} = Q_H - Q_L$$

The working gas of the engine is atmospheric air (treated as ideal gas), and assumed to be working under normal atmospheric pressure of one bar. The heat transfer and the working gas flow friction losses in the engine are insignificant, and should be ignored; but those losses will be taken into account in the later stages.

The classical Schmidt analysis has been the simplest and most widely used method in Stirling engine design. Although subjected to limitations [1], the analysis is still able to provide a lot of useful information. Due to the fact that the working concept is based on an ideal isothermal model; the thermal efficiency should be reduced to the simple Carnot Efficiency [14]. Consequently, it is possible and much more convenient to start the engine design with a classical Carnot Cycle [19] without much error.

$$\text{Ideal thermal efficiency: } (\eta)_{\text{Stirling}} = 1 - \left(\frac{T_{\text{Low}}}{T_{\text{High}}} \right)$$

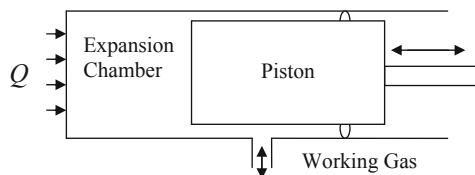


Fig. 5 Stirling engine schematic model

However in actual situation, the maximum achievable efficiency may only reach about 50% of the theoretical ideal Carnot value [16]. In short, the engine suggested for this paper must produce at least as twice as much power in the analysis of the desired load required. By substituting a coefficient, the losses will be more or less compensated. Then, multiplying the equation with heat input which will yield the estimated actual work produce:

$$W_{\text{Stirling}} = \frac{1}{2} Q_{\text{in}} \left[1 - \left(\frac{T_{\text{Low}}}{T_{\text{High}}} \right) \right]$$

From the equation, the temperature difference is directly proportional to the engine performance. Therefore, the solar collector is designed to achieve the highest temperature difference possible.

In the design, the engine needs to cater power requirement to run the desired application and compensate all losses in the system. Therefore, the gross indicated power can be generalized as shown.

$$(W)_{\text{Indicated}} = (W)_{\text{Brake}} + (W)_{\text{Losses, System}}$$

After the initial design, all the parameters will be optimized to maximize thermal efficiency and avoid lose to produce the highest output possible.

4 Results and Discussion

4.1 Solar Collector

The temperature achieved by the solar collector is measured at its receiver when exposed to solar radiation. A parabolic trough with the entire parallel ray from sunlight reflected to a focal line which is formed along the brass rod (receiver). A parabolic trough is not symmetrical to rotation about its focal point. Thus, if the incident beam of parallel rays (solar radiation) is even slightly off normal to the trough aperture, beam dispersion occurs, resulting in spreading of the image at the focal line [18]. Since the trough is manually adjusted, there is always some beam dispersion, which reduces the possible maximum temperature.

The temperature achieved by the collector is shown in Fig. 6. It is obvious that there is fluctuation in the temperature. The fluctuation is caused by the blocking of sun by moving cloud and wind blow. The sun's intensity is reduced when blocked, causing the decrease in temperature. The temperature also drops when there is light wind blow due to greater degree of convective heat loss of the receiver to the surrounding.

For this collector, the sun ray is reflected to a focal point (copper plate). In order to obtain maximal temperature, each mirror is manually adjusted every 15 minutes to track the sun motion. From Fig. 7, it is noticed that the temperature obtained is not

Fig. 6 Temperature measurement of parabolic trough collector, 2005

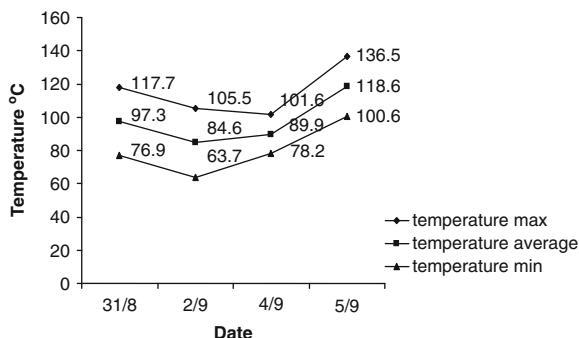
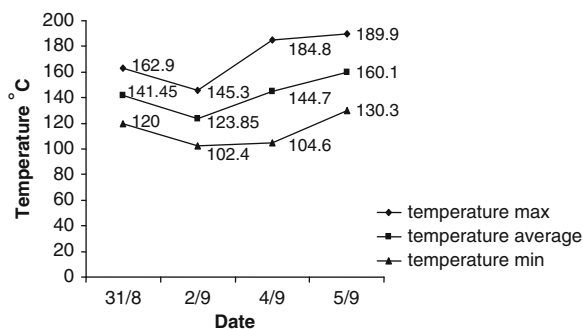


Fig. 7 Temperature measurement of iron glass mirror collector, 2005



constant due to cloudy weather and wind blow. Overall temperature also decreases at late evening because the collector has already reached the maximum adjustable angle.

Basically, the common features between the two collectors are using parabola as its concentrator and they are categorized as concentrating collector which track the sun motion. However, there are few differences between them. Firstly, the reflective material used for the parabolic trough collector is continuous shining aluminum shield and the other one made used of segmented iron glass mirror which form the parabolic shape. And, the reflectance of the shining aluminum shield surface is in the range of 0.8–0.9. The reflectance of the iron glass mirror is above 0.9 which gives better temperature reading as compare with parabolic trough collector [13].

4.2 Stirling Engine Design

Initial design of the engine is started with bore dimension of 50 and 100 mm stroke according to the estimated maximum temperature from the solar collectors. Figures 8 and 9 show the first design drafting for the engine.

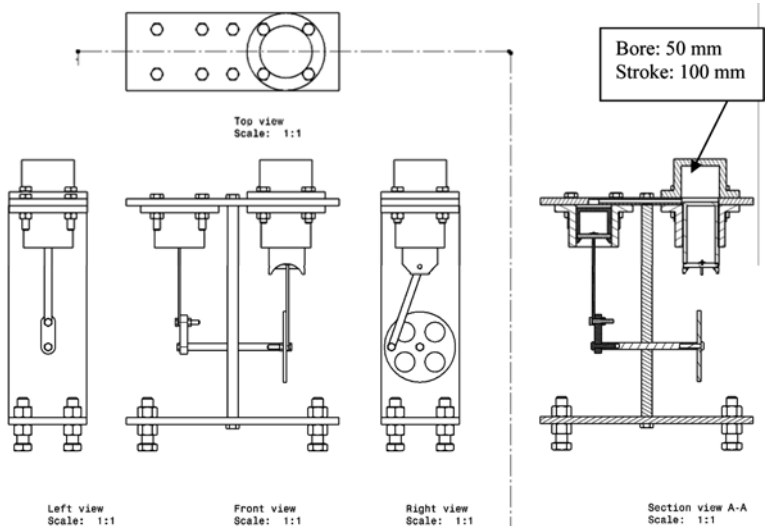
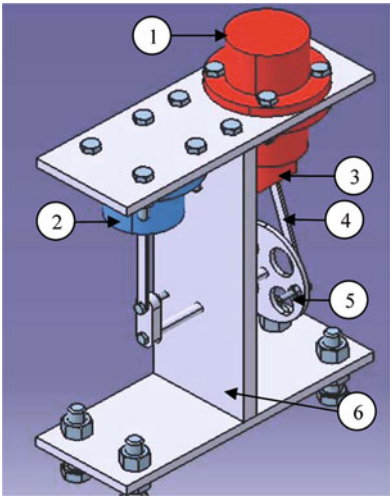


Fig. 8 Two dimensional drawing of stirling engine design in catia

Fig. 9 Three dimensional model of stirling engine in catia. 1. Expansion Cylinder with integrated heater, 2. Compression Cylinder, 3. Piston, 4. Connecting Rod, 5. Fly Wheel, 6. Support Stand



Alpha-type engine was opted for several reasons. Firstly, the simplicity of construction; components are easily fabricated from items available in market and it can be modified easily. The drive mechanism is simple. Integrated heater with expansion cylinder eliminates the need to heat regenerator and minimizes dead volume in the system. Besides that, it is far away from the compression cylinder.

The engine parameters will be optimized in a series of iteration process to acquired the best performance in between the trade offs.

5 Conclusion

Generally, the iron glass mirror collector shows the highest temperature as compared to parabolic trough collector. The highest temperature obtained by iron glass mirror and parabolic trough collector is 189.9 and 136.5°C respectively. This is because the reflectance of mirror is higher than aluminum shield and the iron glass mirror collector has greater concentration ratio. As explained earlier, higher concentration ratio corresponds to higher maximum temperature.

The configuration of the scale model for both collectors is still in testing stage. There are more corrections need to be done to improve the performance.

The engine design is still in the initial stage, all the details are merely for demonstration purpose only. More work will be following to complete the design.

References

1. Abdullah S, Sopian K, Ali Y (2000) Design of an environment friendly solar water pumping system using the stirling engine. Proc. Reg. Conf. Energy Environment, Malayisa, Universiti Tenaga Nasional, Malaysia
2. Abdullah S, Yousif BF, Sopian K (2005), Design consideration of low temperature differential double-acting Stirling engine for solar application. Renewable Energy 30(12);Oct 2005: 1923–1941
3. Banchara K, Somchai W (2005) Optimum absorber temperature of a once-reflecting full conical concentrator of a low temperature differential Stirling engine. Renewable Energy 30(11);Sept 2005:1671–1687
4. Dendane A.(2007) Find the focus of parabolic dish antennas;5. Future Scientists and Engineering of America, FSEA Project Plan (1999). Retrieved November 15, 2009 from http://www.analyzemath.com/parabola/parabola_focus.html.
5. Future Scientists and Engineering of America, FSEA Project Plan (1999)
6. Kreith F, Kreider JF (1978) Principle of solar engineering. McGraw Hill, New York
7. Mills D (2004) Advances in solar thermal electricity technology. Solar Energy 76(1–3); Jan-Mar 2004:19–31
8. Organ AJ (1997) The regenerator and the stirling engine. MEP, London
9. Pongsakorn K, Maung M, Sombat T, Jongjit H, Joseph K, Belkacem Z (2005) Development of a new solar thermal engine system for circulating water for aeration. Solar Energy 78(4); Apr 2005:518–527
10. Senft JR (1993) General analysis of the mechanical efficiency of reciprocating heat engines. J Franklin Inst 330(5); Sept 1993:967–984
11. Kalogirou SA (2004) Solar thermal collectors and application, Department of Mechanical Engineering, Higher Technical Institute, Cyprus
12. Theocharis T, Vasilis G, Katerina M (2003) Technical and economical evaluation of solar thermal power generation. Renewable Energy 28(6);May 2003:873–886
13. Tripanagnostopoulos Y, Yianoulis P, Papaefthimiou S, Zafeiratos S (2000) CPC solar collectors with flat bifacial absorbers. Solar Energy, 69: 171–203
14. Urieli I, Berchowitz D (1984) Stirling cycle engine analysis. Adam Hilger Ltd., Bristol

15. Valdès C (2004) Competitive solar heat engines. *Renewable Energy* 29(11);Sept 2004: 1825–1842
16. Walker G (1980) *Stirling engine*. Claredon Press, Oxford
17. Willard WP (1997) *Engine cycles, engineering fundamentals of the internal combustion engine* (International edn). Pearson Prentice Hall, London
18. Stine WB, Geyer M (2001) *Power from the sun*. <http://www.powerfromthesun.net>
19. Yunus AC, Boles MA (2002) *Thermodynamics, an engineering approach*, 4th edn. McGraw Hill, New York